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Estimating Hydraulic Conductivity Using Pedotransfer Functions

Ali Rasoulzadeh
Water Engineering Dept., College of Agriculture
University of Mohaghegh Ardabili, Ardabil
Iran

1. Introduction

Hydraulic conductivity is an important soil physical property, especially for modeling water flow and solute transport in soil, irrigation and drainage design, groundwater modeling and other agricultural and engineering, and environmental processes. Due to the importance of hydraulic conductivity, many direct methods have been developed for its measurement in the field and laboratory (Libardi et al., 1980; Klute and Dirksen, 1986). Interestingly, comparative studies of the different methods have shown that their relative accuracy varies amongst different soil types and field conditions (Gupta et al., 1993; Paige and Hillel, 1993; Mallants et al., 1997). No single method has been developed which performs very well in a wide range of circumstances and for all soil types (Zhang et al., 2007). Direct measurement techniques of the hydraulic conductivity are costly and time consuming, with large spatial variability (Jabro, 1992; Schaap and Leij, 1998; Christiaens and Feyen, 2002; Islam et al., 2006). Alternatively, indirect methods may be used to estimate hydraulic conductivity from easy-to-measure soil properties. Many indirect methods have been used including prediction of hydraulic conductivity from more easily measured soil properties, such as texture classes, the geometric mean particle size, organic carbon content, bulk density and effective porosity (Wösten and van Genuchten, 1988) and inverse modeling techniques (Rasoulzadeh, 2010; Rasoulzadeh and Yaghoubi, 2011). In recent years, pedotransfer functions (PTFs) were widely used to estimate the difficult-to-measure soil properties such as hydraulic conductivity from easy-to-measure soil properties. The term PTFs were coined by Bouma (1989) as translating data we have into what we need. PTFs were intended to translate easily measured soil properties, such as bulk density, particle size distribution, and organic matter content, into soil hydraulic properties which determined laboriously and costly. PTFs fill the gap between the available soil data and the properties which are more useful or required for a particular model or quality assessment (McBratney et al., 2002). In the other hand PTFs can be defined as predictive functions of certain soil properties from other easily, routinely, or cheaply measured properties. PTFs can be categorized into three main groups namely class PTFs, continuous PTFs and neural networks. Class PTFs calculate hydraulic properties for a textural class (e.g. sand) by assuming that similar soils have similar hydraulic properties; continuous PTFs on the other hand, use measured percentages of clay, silt, sand and organic matter content to provide continuously varying hydraulic properties across the textural triangle (Wösten et al., 1995). In fact, continuous PTFs predict soil properties as a continuous function of one or more measured variables. Neural networks are an “attempt to build a mathematical model that supposedly works in an analogous way to the human brain” and were developed to improve the predictions of empirical PTFs. In brief, a neural network consists of an input, a hidden, and an output layer all containing “nodes”. The number of nodes in input (soil bulk density, soil particle size data) and output (soil hydraulic properties) layers corresponds to the number of input and output variables of the model (Schaap and Bouten, 1996).

PTFs must not be used to predict something that is easier to measure than the predictor. For example, If we measure the water retention curve only to predict saturated hydraulic conductivity (K_s), this is not an efficient PTF, as the cost of measuring a water retention curve is greater than measuring Ks itself (McBratney et al., 2002).

2. Pedotransfer functions for estimating saturated hydraulic conductivity

PTFs have become a ‘white-hot’ topic in the area of soil science and environmental research. PTFs which used to estimate saturated hydraulic conductivity (K_s) were developed using texture classes, the geometric mean particle size, organic carbon content, bulk density and effective porosity as predictor variables. Many PTFs were presented to predict K_s. Here the following PTFs for K_s are considered. All PTFs give K_s in m.s^{-1}. Wösten et al. (1997) presented a function for determining K_s as follows:

$$K_s = 1.15741 \cdot 10^{-7} \exp(x) \tag{1}$$

where x for sandy soil is:

$$x = 9.5 - 1.471(BD^2) - 0.688(Om) + 0.0369(Om^2) - 0.332\ln(CS) \tag{2}$$

and x for loamy and clayey soils is:

$$\begin{aligned} x &= -43.1 + 64.8(BD) - 22.21(BD^2) + 7.02(Om) - 0.1562(Om^2) \\ &+ 0.985\ln(OM) - 0.01332(Clay)(Om) - 4.71(BD)(Om) \end{aligned} \tag{3}$$

where BD is bulk density in g.cm^3, $Clay$ is the percentage of clay, CS is the sum percentage of clay and silt, and Om is percent organic matter.

Wösten et al. (1999) represented another function as follows:

$$K_s = 1.15741 \cdot 10^{-7} \exp(x) \tag{4}$$

where x is:

$$\begin{aligned} x &= 7.755 + 0.0352(Silt) + 0.93(Topsoil) - 0.967(BD^2) - 0.000484(Clay^2) - 0.000322(Silt^2) \\ &+ 0.001/(Silt) - 0.0748/(Om) - 0.643\ln(Silt) - 0.01398(BD)(Clay) - 0.1673(BD)(Om) \\ &+ 0.02986(Topsoil)(Clay) - 0.03305(Topsoil)(Silt) \end{aligned} \tag{5}$$

where BD is bulk density in g.cm^3, $Clay$ and $Silt$ are the percentage of clay and silt, respectively, $Topsoil$ is a parameter that is set to 1 for topsoils and to 0 for subsoils, and Om is percent organic matter.

The Cosby's pedotransfer function (Cosby et al., 1984) was derived based on Sand and Clay contents as:

$$K_s = 7.05556 \cdot 10^{-6} \cdot \left(10^{[-0.6+0.0126(Sand)-0.0064(Clay)]}\right) \tag{6}$$

where *Clay* and *Silt* are the percentage of clay and silt, respectively.
Saxton et al. (1986) suggested a pedotransfer function to estimate K_s as follows:

$$K_s = 2.778 \cdot 10^{-7} \exp(x) \tag{7}$$

where

$$\begin{aligned} x &= 12.012 - 7.55 \cdot 10^{-2}(Sand) \\ &+ \left(-3.895 + 3.671 \cdot 10^{-2}(Sand) - 0.1103(Clay) + 8.7546 \cdot 10^{-4}(Clay^{2)}\right) / \theta_s \end{aligned} \tag{8}$$

where *Clay* and *Sand* are the percentage of clay and sand, respectively, and θ_s is the saturated water content.
Brakensiek et al. (1984) found a relationship between K_s and clay, sand and saturated water content as follows:

$$K_s = 2.778 \cdot 10^{-7} \exp(x) \tag{9}$$

where

$$\begin{aligned} x &= 19.52348(\theta_s) - 8.96847 - 0.028212(Clay) + 1.8107 \cdot 10^{-4}(Sand^2) - 9.4125 \cdot 10^{-3}(Clay^2) \\ &-8.395215(\theta_s{}^2) + 0.077718(Sand)(\theta_s) - 0.00298(Sand^2)(\theta_s{}^2) - 0.019492(Clay^2)(\theta_s{}^2) \\ &+1.73 \cdot 10^{-5}(Sand^2)(Clay) + 0.02733(Clay^2)(\theta_s) + 0.001434(Sand^2)(\theta_s) \\ &-3.5 \cdot 10^{-6}(Clay)(Sand) \end{aligned} \tag{10}$$

All parameters are defined before.
Campbell (1985) presented a pedotransfer function to estimate K_s based on empirical parameter of Campbell's soil water retention function as follows:

$$K_s = 4 \cdot 10^{-5} \left(\frac{1.3}{BD}\right)^{1.3b} \exp\left(-6.9(m_{clay}) - 3.7(m_{silt})\right) \tag{11}$$

where b is an empirical parameter of Campbell's soil water retention function. The coefficient b is derived from the geometric mean particle diameter (mm), d_g, and the standard deviation of mean particle diameter σ_g:

$$b = d_g{}^{-0.5} + 0.2\sigma_g \tag{12}$$

where d_g and σ_g are derived from soil main grain size fractions (m_{clay}, m_{silt} and m_{sand} are clay, silt and mass fractions, respectively) and geometric mean diameter of soil separates (d_{clay}, d_{silt} and d_{sand} are the geometric mean diameters of main grain size fractions in millimeters):

$$d_g = \exp \sum_{i=1}^{3} m_i \ln d_i \tag{13}$$

$$\sigma_g = \exp\left[\sum_{i=1}^{3} m_i (\ln d_i)^2 - \left(\sum_{i=1}^{3} m_i (\ln d_i)\right)^2\right] \tag{14}$$

where m_i is the mass fraction of textural class i, and d_i is the arithmetic mean diameter of class i. The assumption is taken over the three texture classes, sand, silt, and clay. For the three classes normally used in determining texture, d_{clay}=0.001 mm, d_{silt}=0.026 mm, and d_{sand}=1.025 mm. Vereecken et al. (1990) provided a equation for estimating K_s as follows:

$$K_s = 1.1574 \cdot 10^{-7} \exp\left(20.62 - 0.96\ln(Clay) - 0.66\ln(Sand) - 0.46\ln(Om) - 0.00843(BD)\right) \tag{15}$$

Ferrer-Julià et al. (2004) derived a relationship between K_s and sand content of soil as follows:

$$K_s = 2.556 \cdot 10^{-7} e^{(0.0491(Sand))} \tag{16}$$

All parameters in equations 15 and 16 are defined before.

3. Computer models for estimating saturated hydraulic conductivity

3.1 Rosetta

Some PTFs have been incorporated into standalone computer programs like Rosetta (Schaap et al., 2001). Rosetta uses a neural network and bootstrap approach for parameter prediction and uncertainty analysis respectively. Rosetta is able to estimate the van Genuchten water retention parameters (van Genuchten, 1980) and saturated hydraulic conductivity, as well as unsaturated hydraulic conductivity parameters, based on Mualem's (1976) pore-size model (Schaap et al., 2001). Here, Rosetta was used to estimate saturated hydraulic conductivity.

3.2 Soilpar 2

Soilpar 2 provides 15 PTF procedures to estimate soil parameters. The PTFs procedures are classified as point pedotransfer and function pedotransfer. Point PTFs estimate some specific points of interest of the water retention characteristic and/or saturated hydraulic conductivity. Two of these methods also estimate bulk density. Soilpar 2 uses PTFs of Jabro (1992), Jaynes and Tyler (1984), Puckett et al. (1985), and Campbell (1985) to estimate saturated hydraulic conductivity. Function PTFs, which estimate the parameters of retention functions are implemented: Rawls and Brakensiek (1989), to estimate the Brooks and Corey (1964) function parameters; Vereecken et al. (1989), to estimate the van Genuchten (1980) function parameters; Campbell (1985) to estimate the Campbell function parameters (Campbell, 1974)); Mayr and Jarvis (1999), to estimate the parameters of the Hutson and Cass (1987) modification of the Campbell function. All these methods require as input soil particle size distribution and bulk density. The Mayr and Jarvis, and Vereecken et al. methods also require organic carbon content (Acutis and Donatelli, 2003).

4. Pedotransfer functions for estimating unsaturated hydraulic conductivity

One of the most popular analytical functions for predicting unsaturated hydraulic conductivity ($K(\theta)$) is the van Genuchten-Mualem model which is Combination of soil water retention function of the van Genuchten (1980) and Mualem's (1976) pore-size model as follows:

$$K(\theta) = K_s S_e^{0.5}\left[1-\left(1-S_e^{n/(n-1)}\right)^{(1-1/n)}\right]^2 \tag{17}$$

and S_e, is

$$S_e = \frac{\theta(\psi)-\theta_r}{\theta_s-\theta_r} \tag{18}$$

where $\theta(\psi)$ is the measured volumetric water content (cm^3.cm^{-3}) at suction ψ (cm-water); θ_r and θ_s are residual and saturation water content (cm^3.cm^{-3}) respectively, the dimensionless n is the shape factor, and K_s is the saturated hydraulic conductivity.
Other popular function for predicting $K(\theta)$ is the Brooks and Corey (1964) model as follows:

$$K(\theta) = K_s S_e^{(3+2/\lambda)} \tag{19}$$

where λ is the pore size index.
Campbell (1985) proposed a function for determining $K(\theta)$ as:

$$K(\theta) = K_s\left(\frac{\theta}{\theta_s}\right)^{2b+3} \tag{20}$$

where K_s is saturated hydraulic conductivities, θ is measured volumetric water content(cm^3.cm^{-3}), θ_s is the saturation water content (cm^3.cm^{-3}), and b is the slope of ln ψ vs ln θ in the soil water retention curve.
The unsaturated hydraulic conductivity function is particularly difficult and time-consuming to measure directly. So, in many model applications, reliance is often placed on predictions of unsaturated conductivity based on measurements of soil water retention and K_s. Direct measurements of soil water retention and K_s are time-consuming and costly, too. So here, PTFs are used to estimate unsaturated hydraulic conductivity.
Rawls and Brakensiek (1985) provided equations for the estimation of van Genuchten, Brooks - Corey and Campbell parameters as follows:

$$\begin{aligned}LAM &= \exp[-0.7842831+0.0177544*ps-1.062498*por-0.00005304*ps^2-0.00273493*\\&pc^2+1.11134946*por^2-0.03088295*ps*por+0.00026587*ps^2*por^2-0.00610522*\\&pc^2*por^2-0.00000235*ps^2*pc+0.00798746*pc^2*por-0.00674491*por^2*pc]\end{aligned} \tag{21}$$

$$\begin{aligned}\theta_r &= -0.0182482+0.00087269*ps+0.00513488*pc+0.02939286*por-0.00015395*\\&pc^2-0.0010827*ps*por-0.00018233*pc^2*por^2+0.00030703*pc^2*\\&por-0.0023584*por^2*pc\end{aligned} \tag{22}$$

where LAM is pore size index, pc is percent clay, ps is percent sand, por is the porosity.
The unsaturated hydraulic conductivity of van Genuchten parameter (n) is then calculated from the above relations as follow:

$$n = LAM + 1 \tag{23}$$

Campbell's parameter (b) is estimated as follows:

$$b = -1 / LAM \tag{24}$$

In the Brooks and Corey function λ is equal to *LAM*.

5. Computer models for estimating unsaturated hydraulic conductivity

5.1 Rosetta

The van Genuchten parameters, θ_r, θ_s, and n were estimated from measured particle size and bulk density using Rosetta software (Schaap et al., 2001).

5.2 Soilpar 2

Using measured particle size and bulk density data, Campbell model parameter value (b) was estimated using the Soilpar 2 (Acutis and Donatelli, 2003).
Note that, for estimating unsaturated hydraulic conductivity, measured value of θ_s and K_s in the lab were used.

6. Statistical criteria for evaluation of PTFs

6.1 PTFs of saturated hydraulic conductivity

Two following statistical criteria were used for the evaluation of PTFs to estimate saturated hydraulic conductivity based on the approach presented by Tietje and Hennings (1996). Geometric mean error ratio (*GMER*) and geometric standard deviation of the error ratio (*GSDER*) were calculated from the error ratio ε of measured saturated hydraulic conductivity $(K_s)_m$ vs. predicted saturated hydraulic conductivity $(K_s)_p$ values:

$$\varepsilon = \frac{(K_s)_p}{(K_s)_m} \tag{25}$$

$$GMER = \exp\left(\frac{1}{n}\sum_{i=1}^{n}\ln(\varepsilon_i\right) \tag{26}$$

$$GSDER = \exp\left[\left(\frac{1}{n-1}\sum_{i=1}^{n}\left[\ln(\varepsilon_i) - \ln(GMER)\right]^2\right)^{0.5}\right] \tag{27}$$

The *GMER* equal to 1 corresponds to an exact matching between measured and predictive saturated hydraulic conductivity; the *GMER*<1 indicates that predicted values of saturated hydraulic conductivity are generally underestimated; *GMER*>1 points to a general over-prediction. The *GSDER* equal to 1 corresponds to a perfect matching and it grows with deviation from measured data. The best PTF will, therefore, give a *GMER* close to 1 and a small *GSDER*.
Also, other statistical criterion named deviation time (DT) was used to evaluate PTF_S as follows:

$$\log DT = \left(\frac{1}{n} \sum_{i=1}^{n} (\log \varepsilon_i)^2 \right)^{0.5} \tag{28}$$

The DT equal to 1 shows an exact matching between measured and predictive saturated hydraulic conductivity.

6.2 PTFs of unsaturated hydraulic conductivity

Estimated unsaturated hydraulic conductivity using PTFs were compared by calculating modified index of agreement d' (Legates and McCabe, 1999):

$$d' = 1.0 - \frac{\sum_{i=1}^{n} |O_i - S_i|}{\sum_{i=1}^{n} \left(|S_i - O'| + |O_i - O'| \right)} \tag{29}$$

where O_i is the individual observed unsaturated hydraulic conductivity ($K(\theta)$) value at θ_i, S_i is the individual simulated value at θ_i, O' is the mean observed value and n is the number of paired observed–simulated values. The value of d' varies from 0.0 to 1.0, with higher values indicating better agreement with the observations. The interpretation of d' closely follows the interpretation of R^2 for the range of most values encountered (Legates and McCabe, 1999).

7. Estimation saturated and unsaturated hydraulic conductivity using Pedotransfer functions

7.1 Saturated hydraulic conductivity

Study area is located in northwest of Iran in Naghadeh county, Azarbaijanegharbi province, Iran (Fig. 1). The total area of the Naghadeh county is 52100 ha and is located at coordinates 36° 57′ N and 45° 22′ E.

Ten locations in the Naghadeh county was considered and undisturbed soil samples were taken by using a steel cylinder of 100 cm^3 volume (5 cm in diameter, and 5.1 cm in height) from 0-15 cm depth to measure saturated hydraulic conductivity and bulk density. The samples were transported carefully to avoid disturbance. Also, disturbed soil samples were taken using plastic bags to measure particle density, soil texture and organic matter. Saturated hydraulic conductivity was measured by the constant-head method (Israelsen and Hansen, 1962). Samples (steel cylinders) of soil were oven dried at 105ºC and bulk density was calculated from cylinder volume and oven dry soil mass. Particle size distribution (sand, silt and clay percentages) was measured by the hydrometer method. Soil particle density was measured using a glass pycnometer; 10 g air-dried (<2 mm) soil sample was placed into the pycnometer and the displaced volume of distilled water was determined (Jacob and Clarke, 2002). Total porosity was calculated using bulk density (ρ_b) and particle density (ρ_p) according to the following equation:

$$Porosity = 1 - \frac{\rho_b}{\rho_p} \tag{30}$$

Fig. 1. Location of study area.

The organic matter was determined by Walkley and Black rapid titration method (Nelson and Sommers, 1996).
The measured soil properties are shown in Table 1.

Samples	Texture	Bulk density ($g.cm^{-3}$)	Particle density ($g.cm^{-3}$)	Organic matter	Porosity
1	Clay loam	1.37	2.57	2.07	0.46
2	Silty clay	1.21	2.57	3.03	0.52
3	Silty clay loam	1.07	2.58	1.34	0.58
4	Clay loam	1.23	2.61	1.68	0.52
5	Sandy loam	1.43	2.71	1.01	0.47
6	Silty clay loam	1.18	2.55	1.34	0.53
7	Silty clay	1.02	2.49	2.13	0.58
8	Silty clay loam	1.16	2.52	1.46	0.53
9	Silty clay	1.13	2.56	3.36	0.55
10	Silty clay	1.07	2.55	4.09	0.57

Table 1. Measured soil properties in the study area.

Saturated hydraulic conductivities were estimated according to the above mentioned PTFs (Eqs. 1 to 16) as well as Rosetta and Soilpar 2 software and compared to measured K_s of the 10 soils. Note that PTFs of Jabro, Jaynes and Tyler, Puckett et al. which are used in Soilpar 2 2, hereafter named Soilpar 2-Jabro, Soilpar 2- Jaynes – Tyler, and Soilpar 2- Puckett et al., respectively. Figures 2 and 3 show measured vs. estimated values for all models tested. With regard to Figures 2 and 3, it is clear that Soilpar 2-Jabro for estimating K_s was in excellent agreement with the measured value. After Soilpar 2-Jabro, Rosetta could estimate K_s with reasonable accuracy.

Three statistical criteria (Eqs. 25 to 28) were used for the evaluation of PTFs which estimate saturated hydraulic conductivity. Calculated values of *DT, GMER and GSDER* were shown in Table 2. Soilpar 2-Jabro resulted in lower DT (2.91), GMER and GMER equal to 1.13 and 3.06, respectively, performed better than the others PTFs (Table 2). The PTFs of Vereecken et al. tended to high overestimate saturated hydraulic conductivity, while the rest PTFs generally showed underestimate (Table 2).

It is expected that PTFs including organic matter such as Vereecken et al., Wösten et al., and etc could estimate K_s much better than the others PTFs. But the results showed (see Figures 2 and 3 as well as Table 2) these PTFs could not be able to estimate K_s with reasonable accuracy. The organic matter content is an important variable when infiltration rates are estimated in non-saturated soils, but it has less influence in saturated soils. The main explanation is that organic matter mainly affects retention forces (matric potential), the type of forces that almost do not work in saturated soils where forces are basically affected by gravity. For this reason when estimating water retention parameters in soils, organic matter is a valuable variable to use in PTF (Wösten et al., 1999), but the contribution of organic matter content in estimating K_s was very low and it was mainly limited to explain the relationship between soil structure and K_s.

PTF	DT	GMER	GSDER
Wösten et al., 1997	13.25	0.17	7.51
Wösten et al., 1999	6.90	0.21	3.36
Cosby et al.	22.82	0.06	4.74
Sxaton et al.	26.05	0.05	4.15
Brakensiek et al.	73.25	0.021	7.72
Campbell	11.78	0.12	3.61
Vereecken et al.	17925	16813.29	3.22
Ferrer Julia et al.	527	0.002	5.54
Rosetta	9.61	0.13	3.18
Soilpar 2- Jabro	2.91	1.13	3.06
Soilpar 2- Jynes-Tyler	302.6	0.005	11.16
Soilpar 2- Pukett et al.	291.86	0.007	21.42

Table 2. DT, GMER, and GSDER of the estimated K_s compared to measurement for 12 PTFs

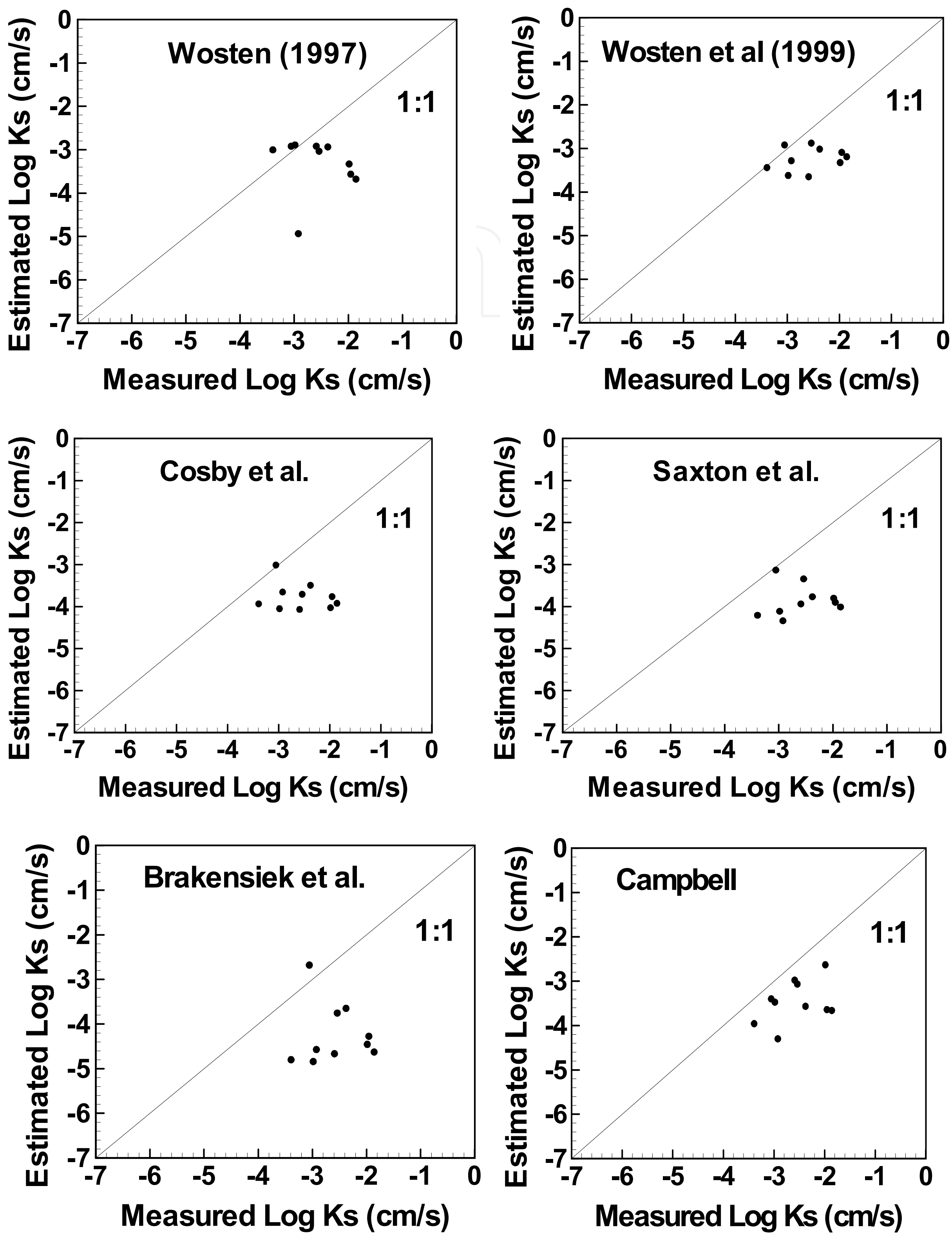


Fig. 2. Measured vs. estimated saturated hydraulic conductivities using PTFs of Wösten et al. (1997), Wösten et al. (1999), Cosby et al., sexton et al., Brakensiek et al. and Campbell for ten soils and 1:1 line

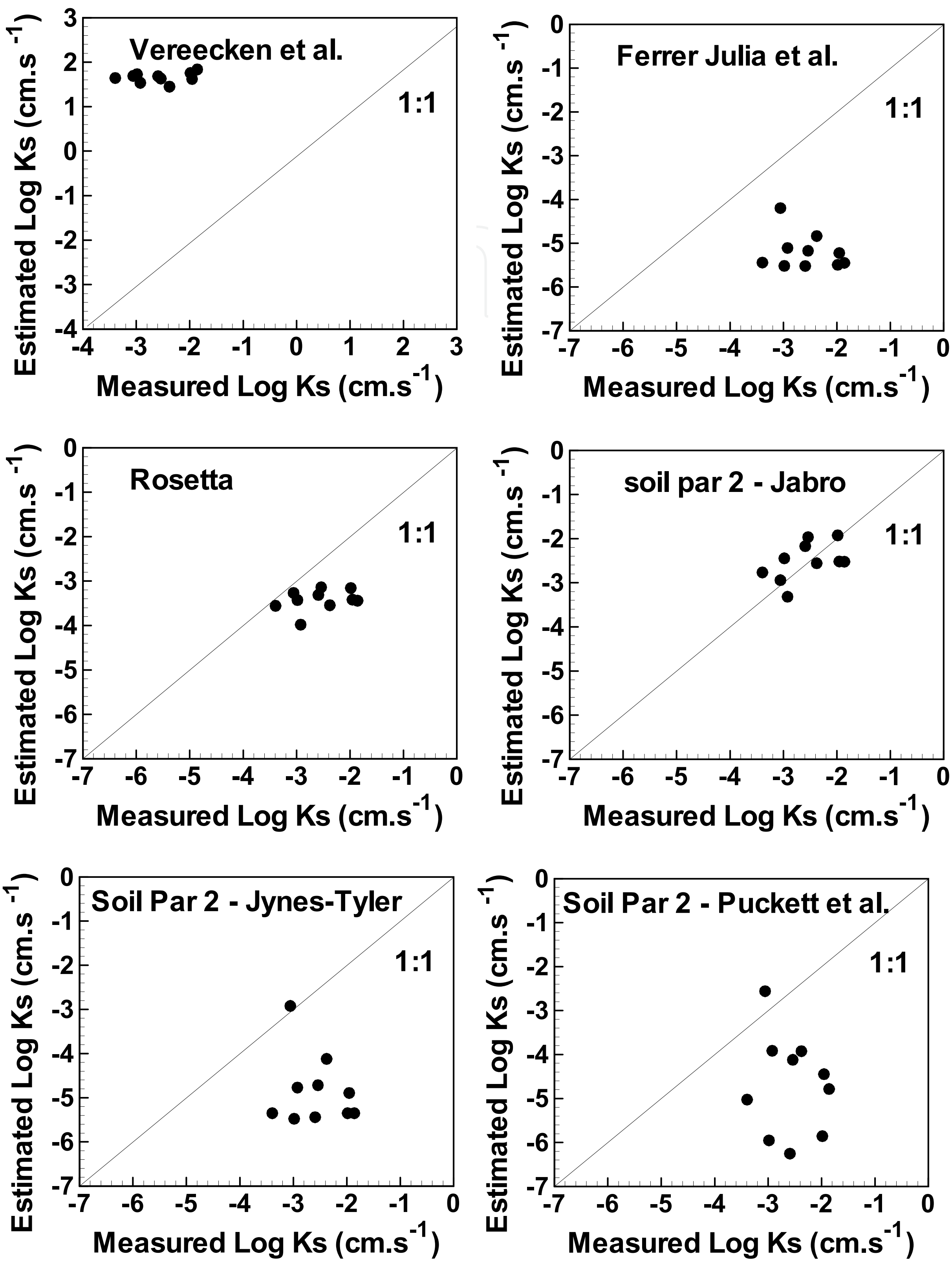


Fig. 3. Measured vs. estimated saturated hydraulic conductivities using PTFs of vereecken et al., Ferrer Julia et al., Rosetta, Soilpar 2-Jabro, Soilpar 2-Jynes-Tyler, and Soilpar 2- Puckett et al. for ten soils and 1:1 line

7.2 Unsaturated hydraulic conductivity

For comparison of the different models in predicting unsaturated hydraulic conductivity of soils, data sets, including data of K_s, measured data of unsaturated hydraulic conductivity, fractions of sand, silt and clay, bulk density of 27 soils were selected from the UNSODA hydraulic property database (Names et al., 1999), and used in the study. The measured soil properties from the UNSODA which used in this study, summarized in Table 3.

Properties	Number	Mean	Min	Max	SD
Bulk density (g. cm^{-3})	27	1.41	0.72	1.8	0.23
Sand (%)	27	49.76	4.30	95.00	30.98
Silt (%)	27	27.91	0.90	70.90	18.20
Clay (%)	27	22.33	1.00	62.00	18.86

Table 3. Mean, standard deviation (SD), Max and Min of soil samples parameters

By using fractions of sand, silt and clay and bulk density, unsaturated hydraulic conductivities ($K(\theta)$) were estimated according to the PTFs of Rawls and Brakensiek (1985) (Eqs. 21 to 24) as well as Rosetta and Soilpar 2 software and compared to measured $K(\theta)$ of the 27 soils. It is noted that PTFs of Rawls and Brakensiek (1985) which were used to estimate parameters of van Genuchten, Brooks - Corey and Campbell functions (Eqs. 17 to 20), hereafter named van Gen-R, B&C-R, and Cam-R, respectively. Also just Campbell model parameter value was estimated using the Soilpar 2, hereafter named Soilpar-Cam.

Figure 4 shows measured vs. estimated $K(\theta)$ by mentioned PTFs. To facilitate comparison of the PTFs, mean value of *modified index of agreement* (d') for the same soil texture classes was calculated (Table 4). With regard to Figure 4 and Table 4, one could conclude that for sand, loamy sand, sandy clay loam, and clay textures, the van Gen-R had the bigger d', indicating its higher accuracy in predicting $K(\theta)$ as compared to the other PTFs. The best PTF for loam, sandy loam, and silty loam textures is the Soilpar-Cam. Wagner et al. (2001) found that the performance of the Campbell model could be improved when the particle size distribution data used in the determining the Campbell parameters are as detailed as possible, while knowledge of only three fractions (clay, silt, and sand) may reduce the function performance considerably.

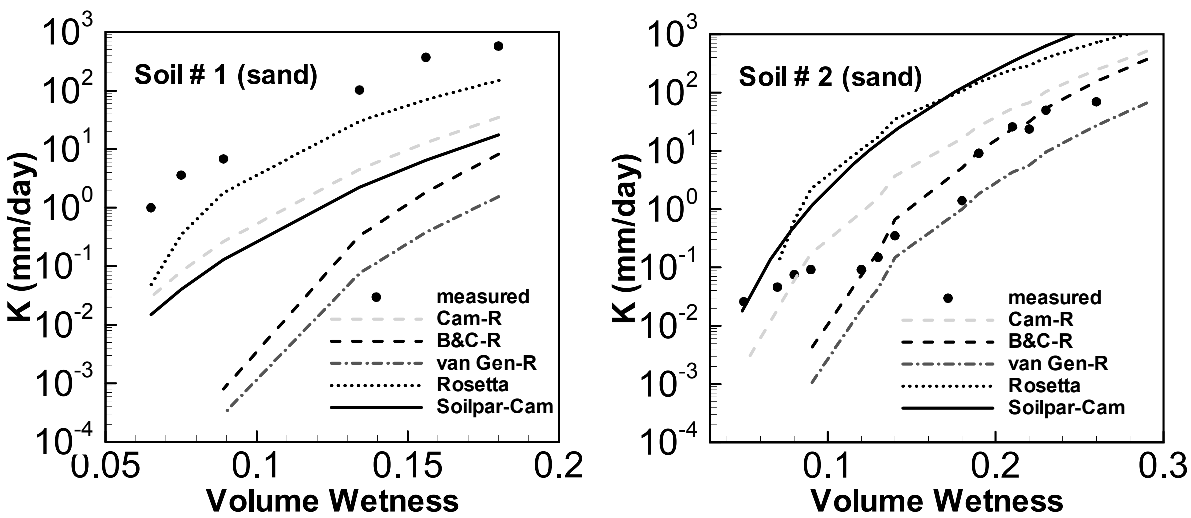


Fig. 4. Comparison of K(θ) measured and estimated by the five PTFs

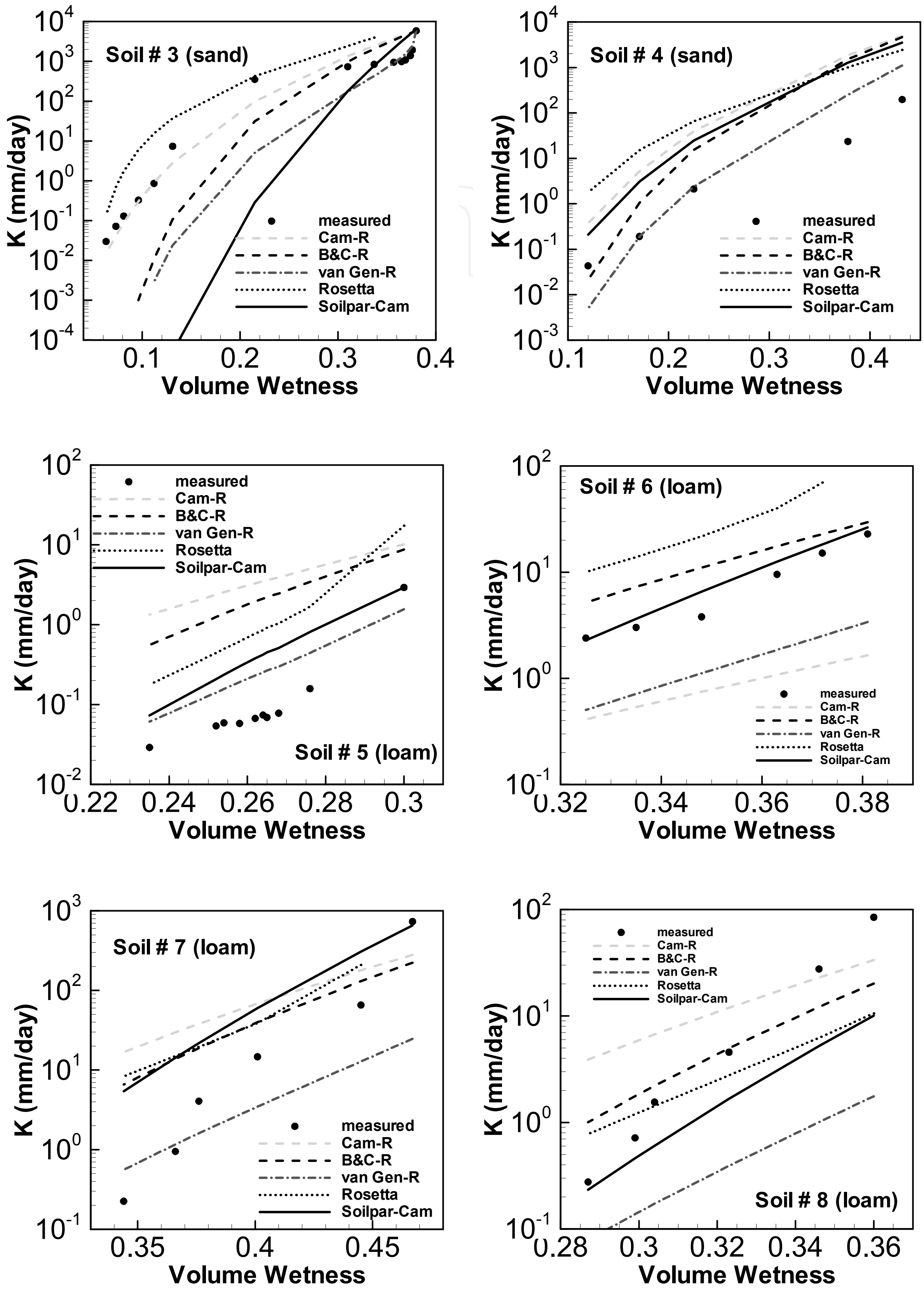
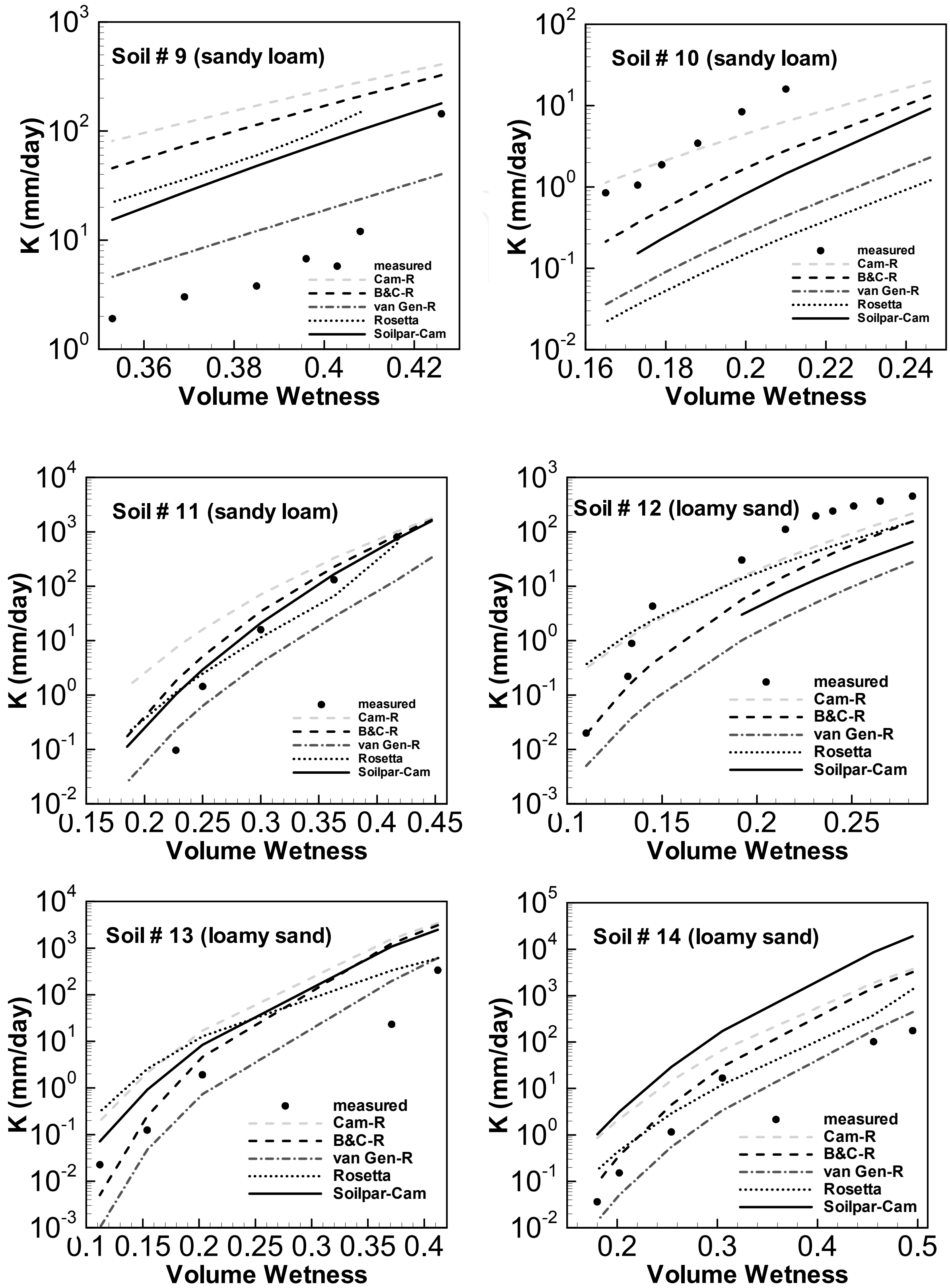


Fig. 4. Continued



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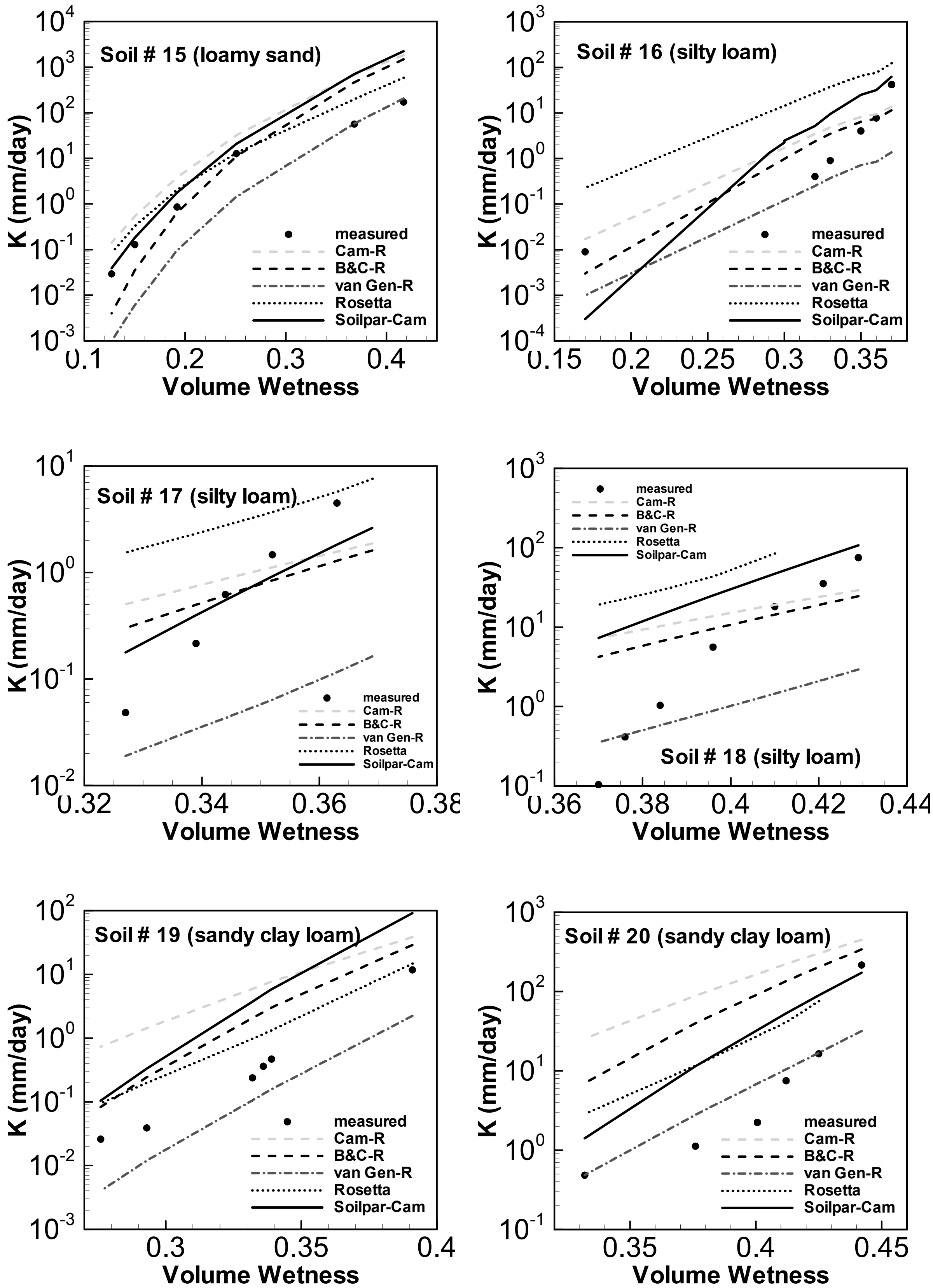

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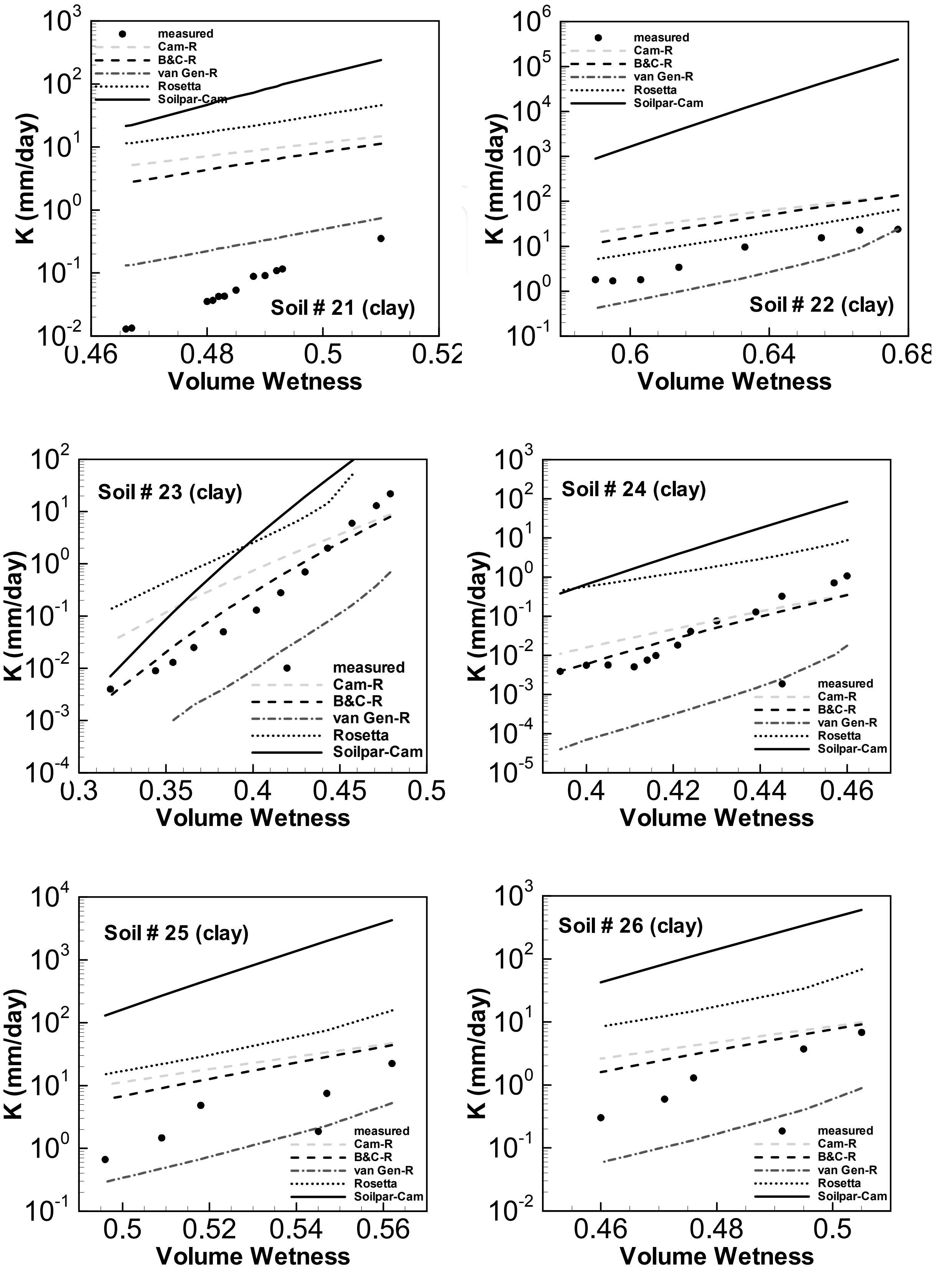

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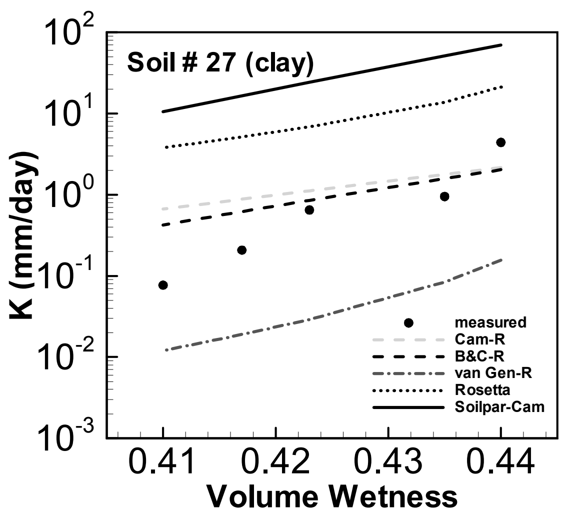


Fig. 4. Continued

Soil texture	Number	Cam-R	B&C-R	van Gen-R	Rosetta	Soilpar-cam
sand	4	0.474	0.485	0.595	0.467	0.425
loam	4	0.399	0.467	0.550	0.318	0.748
sandy loam	3	0.379	0.567	0.593	0.513	0.679
loamy sand	4	0.267	0.281	0.757	0.501	0.302
silty loam	3	0.546	0.578	0.539	0.318	0.590
Sandy clay loam	2	0.311	0.453	0.709	0.535	0.465
clay	7	0.429	0.490	0.513	0.229	0.125

Table 4. Mean value of *modified index of agreement* (d') for the same soil texture

8. Conclusions

Based on the results some of conclusions can be summarized as follows:

- PTFs are a powerful tool to estimate saturated and unsaturated hydraulic conductivity. Because PTFs estimate hydraulic conductivity from easy-to-measure soil properties so they have the clear advantage that they are relatively inexpensive and easy to use.
- The mean of error parameters DT, GMER and GSDER (Table 2) showed that Soilpar 2-Jabro for estimating K_s was in excellent agreement with the measured value in the study area. After Soilpar 2-Jabro, Rosetta could estimate K_s with reasonable accuracy. The PTFs of Vereecken et al. tended to high overestimate saturated hydraulic conductivity. Overestimated K_s by the PTFs of Vereecken et al. makes it a less likely candidate for estimating K_s at the study area or for similar soils. The rest PTFs generally showed underestimate (Table 2).
- The mean value of *modified index of agreement* (d') showed that for sand, loamy sand, sandy clay loam, and clay textures, the van Gen-R had the bigger d', indicating its higher accuracy in predicting $K(\theta)$ as compared to the other PTFs. One can be concluded that Gen-R was approximately good in describing the functional relationship between the soil moisture and unsaturated hydraulic conductivity for mentioned soils. The best

PTF to estimate unsaturated hydraulic conductivity for loam, sandy loam, and silty loam textures was the Soilpar-Cam.

9. References

Acutis M., and M. Donatelli. 2003. SOILPAR 2.00: software to estimate soil hydrological parameters and functions. European Journal of Agronomy 18: 373-377.

Bouma, J. 1989. Using soil survey data for quantitative land evaluation. Advances in Soil Science 9: 177–213.

Brakensiek D.L., W.J. Rawls, and G.R. Stephenson. 1984. Modifying SCS hydrologic soil groups and curve numbers for rangeland soils. ASAE Paper No. PNR-84-203, St. Joseph, MI.

Brooks, R.H., and A.T. Corey. 1964. Hydraulic properties of porous media. Colorado State University, Hydrological paper No. 3, p. 27.

Campbell, G.S. 1974. A simple method for determining unsaturated conductivity from moisture retention data. Soil Science 117: 311-314.

Campbell C.S. 1985. Soil Physics With Basic. Elsevier , New York.149pp.

Christiaens, K., and J. Feyen. 2001. Analysis of uncertainties associated with different methods to determine soil hydraulic properties and their propagation in the distributed hydrological MIKE SHE model. Journal of Hydrology 246: 63– 81.

Cosby B.J., G.M. Hornberger, R.B. Clapp, and T.R. Ginn. 1984. A statistical exploration of the relationship of soil moisture characteristics to the physical properties of soils. Water Resources Research 20 (6): 682-690.

Ferrer-Julià M., T. Estrela Monreal, A. Sánchez del Corral Jiménez and E. García Meléndez. 2004. Constructing a saturated hydraulic conductivity map of Spain using pedotransfer functions and spatial prediction. Geoderma 123: 275-277.

Gupta, R.K., R.P. Rudra, W.T. Dickinson, N.K. Patni, and G.J. Wall. 1993. Comparison of saturated hydraulic conductivity measured by various field methods. Transactions of American Society of Agricultural Engineers 36: 51–55.

Hutson, J.L., and A. Cass. 1987. A retentivity function for use in soil water simulation models. J. Soil Science 38, 105-113.

Islam, N., W. W. Wallender , J. P. Mitchell,S. Wicks, and R. E. Howitt. 2006. Performance evaluation of methods for the estimation of soil hydraulic parameters and their suitability in a hydrologic model. Geoderma, 134:135– 151.

Israelsen, O. W. and V.E. Hansen.1962. Irrigation principles and practices. 3nd ed. John Willey and Sins, Inc. 447 p.

Jabro, J.D., 1992. Estimation of saturated hydraulic conductivity of soils from particle size distribution and bulk density data. Transactions of American Society of Agricultural Engineers 35: 557– 560.

Jacob, H., and G. Clarke. 2002. Methods of Soil Analysis, Part 4, Physical Method. Soil Science Society of America, Inc. Madison, Wisconsin, USA. 1692 p.

Jynes D.B. and E.J. Tyler. 1984. Using soil physical properties to estimate hydraulic conductivity. Soil Science 138: 298-305.

Klute, A., C. Dirksen. 1986. Hydraulic conductivity of saturated soils. In: Klute, A. (Ed.), Methods of Soil Analysis. ASA & SSSA, Madison, Wisconsin, USA, pp. 694–700.

Legates, D.R., G. J. McCabe. 1999. Evaluating the use of ''goodness-of-fit'' measures in hydrologic and hydroclimatic model validation. Water Resources Research 35: 233–241.

Libardi, P.L., K. Reichardt, D.R. Nielsen, and J.W. Biggar. 1980. Simple field methods for estimating soil hydraulic conductivity. Soil Science Society of America Journal 44: 3–7.

Mallants, D., D. Jacques, P. Tseng, M.T. van Genuchten, and J. Feyen. 1997. Comparison of three hydraulic property measurement methods. Journal of Hydrology 199: 295–318.

Mayr, T., and N.J. Jarvis. 1999. Pedotransfer function to estimate soil water retention parameters for a modified Brooks -Corey type model. Geoderma 91, 1-9.

McBratney, A.B., B. Minasny, S.R. Cattle, and R. W. Vervoort. 2002. From pedotransfer functions to soil inference systems. Geoderma 109: 41-73.

Mualem, Y. 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resources Research 12: 513–522.

Nemes, A., M. Schaap, and F. Leij. 1999. the UNSODA unsaturated soil hydraulic database (Version 2.0).US Salinity Laboratory, Reverside,CA.

Nelson, D. W., and L. E. Sommers. 1996. Total carbon, organic carbon, and organic matter. In: D. L. Sparks (Ed.), Methods of Soil Analysis. Part 3: Chemical Methods. Soil Science Society of America, Madison, WI, 961-1010

Paige, G.B., and D. Hillel. 1993. Comparison of three methods for assessing soil hydraulic properties. Soil Science 155: 175–189.

Rawls, W. J. and D. L. Brakensiek.1985. Prediction of soil water properties for hydrologic modeling. In: E. Jones and T. J. Ward (eds.) Watershed Management in the Eighties, Proceedings of a symposium ASCE. 30 Apr.- 1 May. 293-299.

Rawls, W.J., and D.L. Brakensiek. 1989. Estimation of soil water retention and hydraulic properties. In: Morel, S. (Ed.), Unsatured Flow in Hydrologic Modeling. Theory and Pratice. Kluwer academic publishers, pp. 275-300.

Puckett W.E., J.H. Dane, and B.F. Hajek. 1985. Physical and mineralogical data to determine Soil hydraulic properties. Soil Science Society of America Journal 49: 831-836.

Rasoulzadeh, A. 2010. Evaluation of parameters estimation using inverse method in unsaturated porous media, 10th International Agricultural Engineering Conference, Bangkok, Thailand, December 7-10.

Rasoulzadeh, A. and A. Yaghoubi. 2011. Study of cattle manure effect on soil hydraulic properties using inverse method. 2nd International Conference on Environmental Science and Technology (ICEST), Singapore, February 26-28.

Saxton K.E., W.J. Rawls, J.S. Romberger, and R.I. Papendick. 1986. Estimating generalized soil water characteristics from texture. Soil Science Society of America Journal, 50: 1301-1036.

Schaap, M.G., and W. Bouten. 1996. Modeling water retention curves of sandy soils using neural networks. Water Resources Research 32: 3033–3040.

Schaap, M. G., and F. J. Leij. 1998. Using neural networks to predict soil water retention and soil hydraulic conductivity. Soil & Tillage Research 47: 37-42.

Schaap M.G., F.J. Leij, and M.T. van Genuchten. 2001. ROSETTA: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. Journal of Hydrology 251: 163-176.

Tietje, O., and V. Hennings. 1996. Accuracy of the saturated hydraulic conductivity prediction by pedo-transfer functions compared to the variability within FAO textural classes. Geoderma 69, 71–84.

van Genuchten, M.T. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal 44: 892–898.

van Genuchten, M.T., and D.R. Nielsen. 1985. On describing and predicting the hydraulic properties of unsaturated soils. Ann. Geophys. 3: 615– 628.

Vereecken H., J. Maes, and J. Feyen. 1990. Estimating unsaturated hydraulic conductivity from easily measured soil properties. Soil Science 149: 1-12.

Vereecken, H., J. Maes, J., Feyen, and P. Darius. 1989. Estimating the soil moisture retention characteristics from texture, bulk density and carbon content. Soil Science 148: 389-403.

Wagner, B., V.R. Tarnawski, V. Hennings, U. Müller, G. Wessolek, and R. Plagge. 2001. Evaluation of pedo-transfer functions for unsaturated soil hydraulic conductivity using an independent data set. Geoderma 102: 275-297.

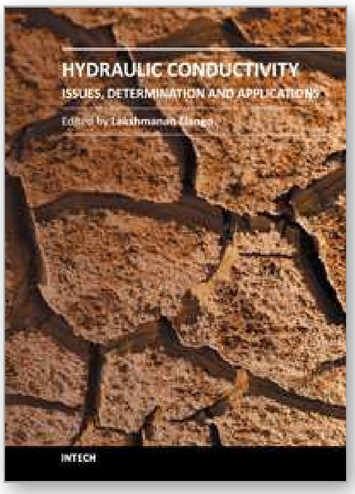
Wösten, J.H.M., P.A. Finke, and M.J.W. Jansen. 1995. Comparison of class and continuous pedotransfer functions to generate soil hydraulic characteristics. Geoderma 66: 227–237.

Wösten, J.H.M., and M.T. van Genuchten. 1988. Using texture and other soil properties to predict the unsaturated hydraulic conductivity. Soil Science Society of America Journal 52: 1762–1770.

Wösten J.H.M. 1997. Pedotransfer functions to evaluate soil quality. In:Gegorich, E.G., Carter, M.R. (Eds.), Soil Quality for Crop Production and Ecosystem Health. Developments in Soils Science, vol. 25, Elsesevier, Amesterdam 221-245.

Wösten J.H.M., A. Lilly, A. Nemes, and C. Le Bas. 1999. Development and use of a database of hydraulic properties of European soils. Geoderma 90: 169-185.

Zhang, S., L. Lövdahl, H. Grip, and Y. Tong. 2007. Soil hydraulic properties of two loess soils in China measured by various field-scale and laboratory methods. Catena 69: 264-273.



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There are several books on broad aspects of hydrogeology, groundwater hydrology and geohydrology, which do not discuss in detail on the intrigues of hydraulic conductivity elaborately. However, this book on Hydraulic Conductivity presents comprehensive reviews of new measurements and numerical techniques for estimating hydraulic conductivity. This is achieved by the chapters written by various experts in this field of research into a number of clustered themes covering different aspects of hydraulic conductivity. The sections in the book are: Hydraulic conductivity and its importance, Hydraulic conductivity and plant systems, Determination by mathematical and laboratory methods, Determination by field techniques and Modelling and hydraulic conductivity. Each of these sections of the book includes chapters highlighting the salient aspects and most of these chapters explain the facts with the help of some case studies. Thus this book has a good mix of chapters dealing with various and vital aspects of hydraulic conductivity from various authors of different countries.

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InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
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No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821